Air Force Research Laboratory

Quantum Computation for Physical Modeling Workshop 2000 Contributed Talks*

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1 Session I: Nuclear Magnetic Resonance Spectroscopic Technologies

Wednesday the 18th of October from 9:30am to 11:45am

1.1 NMR Approaches to Quantum Information Processing

David G. Cory, Departments of Nuclear Engineering and Physics, Massachusetts Institute of Technology

If one is ever built, a quantum computer will exploit the superposition principle to solve certain problems much more efficiently than any known algorithm for their classical counterparts. Important problems that benefit from such speedups include factoring large numbers, combinatorial searches, and simulations of quantum systems. I will describe the implementation of small prototype quantum information processors based on Nuclear Magnetic Resonance and current efforts to extend these to solid state NMR.

1.2 Improved Coherent Quantum Control of NMR Systems

Evan M. Fortunato, Marco A. Pravia, Nicolas Boulant, Grum Teklemariam, Timothy F. Havel, David G. Cory, Departments of Nuclear Engineering and Physics, Massachusetts Institute of Technology

Although theoretical advances in quantum information processing (QIP) have shown the potential power of quantum computation, experimental implementations are comparatively primitive. The main obstacle to creating a quantum computer is to obtain precise coherent control of a physical system that is isolated from the decohering effects of its environment. While nuclear magnetic resonance (NMR) techniques have been used to demonstrate control over small quantum systems, traditional methods utilizing low-power rf fields which slowly modulate the system have significant draw backs. Control can be improved with detailed knowledge of the system's internal Hamiltonian and the use of high power rf fields that strongly modulate the system. This talk introduces methods which allow for the creation of short (300us), selective pulses that average out the undesired evolution of the internal Hamiltonian to implement true single-bit quantum logic gate operations.

Numerical algorithms to determine the shape, simulated fidelities of the gates, and experimental issues involved with implementing these pulses are discussed. Experimental results and simulations of small perturbations, in either the internal Hamiltonian, or the applied rf, will be presented.

1.3 NMR Implementations of Quantum Information Processing

Marco A. Pravia, Nicolas Boulant, Evan M. Fortunato, Grum Teklemarium, Yaakov Weinsten, Timothy F. Havel, David G. Cory, Departments of Nuclear Engineering and Physics, Massachusetts Institute of Technology

In the past four years, nuclear magnetic resonance (NMR) techniques have provided an important experimental avenue for the exploration of quantum information processing. In this talk, we report on the first quantum information processing (QIP) experiments performed using high-power shaped pulses that perform single-spin rotations faster and more accurately than typical techniques. The new methods were used to implement an entanglement eraser and a quantum Fourier transform on a three-spin molecule. In another experiment, this time on a four-spin molecule, we entangled two spins and transferred the state to two other spins. The results demonstrate the utility of NMR methods to examine quantum information primitives, and serve to illustrate the increased level of control achieved using strong modulation. Future work will focus on applying control methods to larger spins systems and to explore new applications, including the implementation of quantum lattice-gas algorithms to solve differential equations.

1.4 Massively Parallel NMR Spectrometers for Quantum Computing Applications

Bruce Hammer, University of Minnesota

The concept of developing a quantum computer based on the NMR phenomenon utilizes nuclear spins as a physical implementation of a quantum memory register, i.e. qubit. Through the interaction of RF pulses with spin couplings and chemical shifts on a molecule unitary transformations can be applied to an ensemble of molecules. Thus, quantum computation is possible through the use of RF pulses. Present-day NMR computations takes place in a bulky and very expensive NMR spectrometer on one sample, thus only three or four qubit are presently feasible with this approach. Our goal is to utilize state-of-the-art RF microelectronic fabrication to place multiple NMR spectrometers on a silicon wafer. This concept presents a number of barriers for a successful technical implementation. Magnetic susceptibility, RF phase stability, quantum-classical linkages for read-out and the fabrication of micro RF coils represent some of the obstacles. The ultimate physical realization of a massively parallel NMR spectrometer will be discussed.

2 Session II: Quantum Lattice-Gas Algorithms

Thursday the 19th of October from 1:45pm to 2:45pm

2.1 Physical Quantum Algorithms

David A. Meyer, University of California San Diego

Feynman originally conceived of quantum computers as a means to simulate quantum systems for which there was no classical simulation method known. In this talk I'll review the status of this problem and discuss current (theoretical) results on physical simulations by quantum lattice gas automata and quantum gate arrays. One should also ask whether physics can inspire quantum algorithms for classical problems, so I'll conclude by suggesting a few possibilities perhaps deserving investigation.

2.2 Quantum Lattice-Gas Automata

Bruce M. Boghosian Department of Mathematics, Tufts University

Quantum lattice-gas automata are quantum mechanical models on a discrete configuration space. Feynman developed one such model for the Dirac equation in one spatial dimension, and presented it as an exercise in his book on path integrals. More recently, it has been noted that these models provide a rather general paradigm for the simulation of quantum mechanical systems on a quantum computer, and this has spurred development of new such models for the Schroedinger equation in multiple spatial dimensions, and for multiple particles, with both applied and interparticle interaction potentials. This talk will survey these types of models and speculate as to what the smallest meaningful quantum mechanical simulation of one would entail and accomplish.

3 Session III: Potential Solid State Technologies

Wednesday the 18th of October from 3:00pm to 4:00pm

3.1 Solid-State Quantum Computing in Semiconductor Structures

Vladimir Privman, Clarkson University

We present our theoretical program of study of nuclear-spin and other solid-state quantum computing (QC) models. We aim at developing techniques for general evaluation of decoherence and relaxation in solid-state systems which are candidate for QC implementations. Results include a systematic investigation of spin interactions and dephasing (decoherence) in semiconductor quantum wells and heterojunctions, with initial applications for nuclear spins. Our starting system for these theoretical studies have been nuclear spins in semiconductor layered structures, in the regime of low temperature and high magnetic field. The electron system is then in the quantum Hall effect state for certain magnetic field values. Indirect hyperfine coupling between two nuclear spins is considered as a possible mechanism of realization of a two-qubit entangled system.

In a few- or multi-qubit system, there will be various time scales of quantum evolution. Interaction with external NMR or ESR field causes each spin (qubit) to evolve on the time scale T(ext). Spin-spin interactions result in evolution on the time scale T(int). In addition, there will be relaxation (thermalization) owing to interactions with the "rest of the universe," on time scales of order T(1), as well as quantum decoherence/dephasing, present even at zero temperature, on time scales T(2). For coherent operation of a QC, one needs T(1), T(2) $\gg$ T(int), T(ext). We report our recent extensive many-body calculations leading to estimates of T(2) and T(int), as well as survey other known results and conditions, theoretical and experimental, for the relevant time scales.

3.2 Type II Quantum Computing in Spectrally Selective Solids

M.S. Shahriar and Seth Lloyd, Res. Lab. of Electronics, MIT, Phillip R. Hemmer, AFRL, Hanscom, MA

Our goal is to develop a solid state quantum computer that is scalable to a large number of qubits. Our approach is to use spectral hole-burning (SHB) materials for which a large number of individual atoms can be selectively addressed using lasers. However, the qubits will be the spins of individual active atoms, which are known to have long coherence lifetimes in these materials. Qubit initialization and single-qubit manipulations will be performed using laser excited Raman transitions. Because of the large optical Rabi frequencies, we anticipate being able to perform > 1000 single-qubit operations within the coherence lifetime. Two-qubit, nonlinear operations will be performed using either cavity QED or optical dipole coupling in conjunction with laser excited Raman transitions. So far, we have demonstrated the ability to achieve near 100

4 Session IV: Persistent Current Qubits Using Superconducting Technologies

Wednesday the 19th of October from 9:00am-10:00am

4.1 The Superconducting Persistent Current Qubit

Terry Orlando, MIT Department of Electrical Engineering and Computer Science

Microwave spectroscopy experiments have been performed on two quantum levels of the persistent current qubit. This qubit is a macroscopic superconducting loop with three Josephson junctions. Level repulsion of the ground state ("0") and the first excited state ("1") is found where two classical persistent-current states with opposite polarity are degenerate, indicating symmetric and antisymmetric quantum superpositions of macroscopic states. The two classical states have persistent currents of about a microamp and correspond to the center-of-mass motion of millions of Cooper pairs. The sources of decoherence and the use of coupled qubits for quantum computation will also be discussed.

4.2 Quantum Computing with Superconduction Electronics

Karl Berggren and Michael O'Hara, MIT Lincoln Laboratory and Daniel Nakada and Terry Orlando, MIT Department of Electrical Engineering and Computer Science

Two recent demonstrations have created coherent superpositions of macroscopic currents, counter-propagating in a superconducting loop. These results suggest that coherent quantum control of persistent-current states in a superconductor is readily achievable, and may be a viable path to large-scale quantum computing. The question of practical implementation of this technology in a quantum computer immediately raises the issue of interfacing to classical control circuits; any quantum computer will require sophisticated classical control circuits to prepare the initial state of the quantum register and read out the classical data. Superconductive niobium electronics have been used for high-speed classical electronics for many years and bring several advantages when considered as a candidate for control electronics for superconductive qubits. These advantages are : 1) inherently fast operating speed, 2) compatibility with cryogenic operation, 3) ease of integration with a SQUID magnetometer. We will discuss the merits of this approach, and present results of our recent efforts to integrate quantum devices with classical circuits.

5 Session V: Quantum Algorithms

WEDNESDAY THE 19TH OF OCTOBER FROM 10:15AM-11:15AM

5.1 Modeling and Simulating Fragments of Quantum Algorithms in a Spin Quantum Computer with a Large Number (up to 1000) of Qubits

Gennady Berman, Los Alamos National Laboratory

To build a working quantum computer with many qubits many dynamical issues must be modeled and simulated. We have developed analytic and numerical tools to simulate in a controlled way the dynamics of simple quantum logic operations with a large number of qubits (up to 1000). Our methods apply to most quantum computers now being considered. We have applied our approach to a one-dimensional nuclear spin chain quantum computer. A uniform external magnetic field gradient is used to enable selective spin excitations. Quantum logic operations are produced by resonant electromagnetic pulses. The spins interact with their nearest neighbors through the Ising and Heisenberg interactions. Using our software, we have simulated algorithms for the creation of entangled states of remote qubits, for teleportation and for a quantum full adder. For quantum teleportation, quantum logic gates are implemented using selective π- and $\frac{\pi}{2}$-electromagnetic pulses. This sequence of pulses is combined with single-spin measurements to simulate teleportation. To implement a quantum full adder in a spin chain quantum computer, we use selective electromagnetic π-pulses. To add L-qubit numbers, our protocol requires 2L+1 qubits and less than 27 L electromagnetic pulses. Our method minimizes unwanted non-resonant effects in a controlled way. Our approach can be used to optimize the design of quantum computers and to estimate their relative experimental performance.

5.2 Quantum Algorithms for Fermionic Simulations

Gerard Ortiz, Los Alamos National Laboratory

We investigate the simulation of fermionic systems on a quantum computer. We show in detail how quantum computers avoid the dynamical sign problem present in classical simulations, therefore reducing a problem of exponential complexity into one of polynomial complexity. The key to our demonstration is the spin-particle connection (or generalized Jordan-Wigner transformation) that allows exact algebraic invertible mappings of operators with different statistical properties. We give an explicit implementation of a simple problem using a quantum computer based on standard qubits.